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Finite element simulation of robotic origami folding

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A B S T R A C T

In this paper, we focus on some aspects of the finite element simulations of robotic paper folding and the reconstruction of models from the origami crease patterns by the robot arms. The paper highlights the simulation problems, which should be solved in developing our recent study in mechanical and geometrical design of the origami-performing robot. The basic premise underlying the study is that folding operations with the origami crease patterns are considered as the functions of the mechanical systems such as a robot. Manipulations with the foldable objects, such as a sheet of paper (the origami crease pattern), by the robot arms in the simulation environment lead to understanding the design of the origami-performing robot without testing physical prototypes at each design stage. In this case, dynamic and kinematic behavior of the robot arms in forming the 3D origami objects is modelled by using the finite element method (FEM) in LS-DYNA solver. For simulating, two forms of origami are considered: flexible, if bending is used for paper folding, and rigid, if origami patterns are considered as the kinematic systems. Results of the simulation are presented and provided by the illustrations.

1. Introduction

Since origami has many advantages, its applications are now used widely in industry and everyday life. Origami starts from a two-dimensional layer and transforms to the three-dimensional structure via folding. Origami principles have broad and varied applications: from solar arrays [20] and building facades [7] to robotics [9,17], mechanisms in stent grafts [12], and DNA-sized boxes [1]. The materials and methods, which are used for fabricating, actuating, and assembling these products, can vary greatly with a length scale. Large-scale origami structures can be constructed from the thickened panels connected by hinges and can be actuated with mechanical forces. The benefit of origami structures is their ability to support weight with enough stiffness and to pack a large surface area into a compact flat shape. With developing the origami structures, the material using for folding currently is not only an ordinary paper with a small thickness 0.1 mm. Special paper materials, such as cardboard or coated paper, which thickness is bigger (1–2 mm), are used for forming origami structures to increase the stiffness and still keep the lightweight structure. There are some approaches for folding the origami patterns with different thickness [6] and developing self-folding machines [9]. Hence, building a robot that can help people to fold the target origami patterns is a trend all over the world.

The experimental folding machine presented by [2] includes a blade press for forming the creases and a working table. Two robot hands are used for folding paper in Elbrechter et al. [8]. The authors apply a method for real-time detection,

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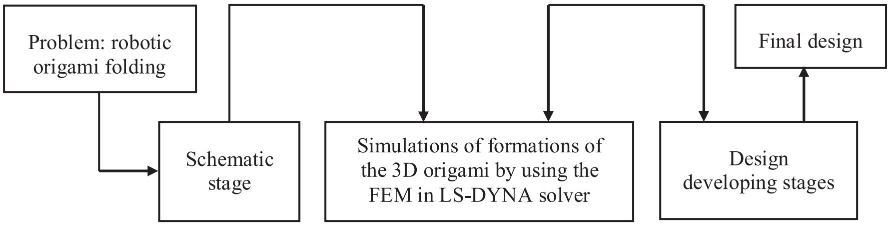

Fig. 1. Scheme of the iterative design process.

physical modelling of paper, and suggest an approach to recognize the shape of a sheet of paper. In [18] the robot design for folding the origami model, which uses a rubber ball to form creases, is described; that robot design should be redesigned for each origami model.

To our knowledge, there are no publications related to the simulation-based design for the origami-performing robotic system. In the previous publication [19], we have introduced our vision and detail investigation of the simulation-based design of the origami-performing robot, where each origami folding operation is considered as a function of the mechanical systems such as a robot and performing the folding operations by the robotic arms by numerical simulation. The preliminary simulation results show that the proposed approach for designing the origami-performing robot can be considered as a basis for the design of the realistic robot. The design of a robot that is based on experiment only is difficult, expensive, and time-consuming. We focus on the finite element (FE) simulation of paper folding and forming the 3D origami models from the 2D origami crease patterns by the robot arms with the aim to design the origami-performing robot.

The present paper highlights the calculation problems that are related to FE simulation of forming the origami models by the robot arms such as: a simulation of folding the multi-intersecting origami patterns, kinematic modelling the cardboard origami patterns, planning the folding operations, and folding conditions for the real crease patterns. The FEM in LS-DYNA software [14] allows us to study the complicated geometrical shapes and simulate the performance of the formation of the origami models by the robot arms.

The main contributions in this paper are:

(a) Meshing template to solve FE problems related to the strong deformed sheet of paper: multi-thickness computational model (the origami multi-intersecting crease pattern);
(b) The FE simulation approach for the production of the cardboard origami-based structures with straight and curve folds by the robotic arms;
(c) Generating unique folding sequences from origami crease pattern for robot manipulation.

The presented simulation results of forming the 3D origami objects by robotic arms show the applicability of the suggested approach for the origami-performing robot design.

The following is a brief overview of this paper: Section 1 introduces the FE simulation approach for the design of the robotic system for the origami applications. In Section 2, fundamentals of the approach are described. Description of the general computational models for the flexible origami is provided in Section 3. The simulation problems related to the formation of the multi-intersecting origami crease patterns are discussed in Sections 4 and 5. Section 6 presents virtual testing of forming origami models by the origami- performing robot. Discussion and conclusions can be found in Section 7.

2. Fundamentals of method

The engineering design process includes series of steps for creating functional product. In this section, we briefly describe the simulation-based method for mechanical and geometrical design of the origami-performing robot (Fig. 1). FE simulations and mechanical engineering problems, which were solved in the previous phase of our research, are explained here. The suggested robot design process includes three main stages: schematic design that presents a conceptual design, computational modelling by using the FEM, and design development that includes the modifications of the schematic design. The final design can be approved after virtual testing and analysis of the simulation results for the different kinds of the origami models. Modifications of the schematic design depend on the correctness of dynamic and kinematic behavior of the robot at the time of FE simulations of the formation of origami.

2.1. The robot description

The final robot design [19] includes a working table (a base and rotating part) and two robotic arms: one folding and one holding (Fig. 2). For the folding arm with the fingers (the grippers), the main operations are: grasping and rotating a sheet of paper around crease lines. The holding arm with the holding fingers (the holders) is used to fix a sheet of paper on the working table. The working table is designed with the sharp edges to ensure good physical contact between the sheet of paper and the working table when the sheet of paper is bent around crease. We define crease placement at the sharp edge